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Limits on Light Right-Handed Neutrinos

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ABSTRACT

We investigate the possibility that the right-handed Majorana electron neutrino mass $m_{\nu_{eR}}$ lies in the range between a few tens and a few hundred MeV. Existing data of $\pi \to e\nu$, of neutrinoless double β-decay and the cosmological bound on the neutrino lifetime are studied to impose correlated bounds on $m_{\nu_{eR}}$ and m_{W_R}. For $m_{\nu_{eR}} \sim 50$-100 MeV we find $m_{\nu_{eR}}/m_{W_R} \sim m_e/m_{W_L}$.

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The purpose of this note is to investigate the phenomenological consequences and the present experimental limits of a possible existence of a right-handed neutrino with a mass in the range between a few tens and a few hundred MeV. We first describe the theoretical motivation of our study and then analyze the above possibility in detail.

The left-right symmetric models of the electroweak interactions, based on the gauge group $SU(2)_L \times SU(2)_R \times U(1)$, were shown to lead quite naturally to a very light left-handed neutrino and to a rather heavy right-handed neutrino.[1] Assuming the neutrino to be a Majorana particle, the left and right mass eigenstates can be shown to be related by[2,3]

$$m_{\nu_L} \simeq \frac{m_{\nu_D}^2}{m_{\nu_R}} \qquad (1)$$

Basically ν_R obtains a large Majorana mass at the scale of left-right symmetry breaking, while ν_L gets a small mass induced by the Dirac term m_{ν_D} which mixes the two helicity states. $m_{\nu_{eR}}$ and $m_{\nu_{eD}}$ are correspondingly related to the mass of the right-handed gauge boson and the electron mass via the ratios of suitable gauge and Yukawa couplings:[1]

$$m_{\nu_{eR}} \simeq \frac{h^M}{g} m_{W_R}$$

$$m_{\nu_{eD}} \simeq \frac{h^D_\nu}{h^D_e} m_e \qquad (2)$$

The authors of Ref. 1 assume for simplicity that $h^M \sim g$, $h^D_\nu \sim h^D_e$ and thereby predict

$$m_{\nu_{eL}} \simeq \frac{m_e^2}{m_{W_R}} \qquad (3)$$

Using the present bound $m_{W_R} \geq 3m_{W_L}$[4] they then obtain the bounds $m_{\nu_{eL}} \leq 1$ eV and $m_{\nu_{eR}} \geq 230$ GeV.

Here we suggest to adopt a more conservative approach by keeping h^M and g, or alternatively $m_{\nu_{eR}}$ and m_{W_R}, unrelated. After all if the scales of m_e and m_{W_L}, the left-handed analogs of the latter, are set by the vacuum expectation value of a single scalar field, the corresponding Yukawa and gauge couplings (h^D_e, g) differ by five orders of magnitude. The forthcoming phenomenological study will indicate that this may just as well be the case for h^M and g.

We let h^D_ν and h^D_e differ by up to an order of magnitude. This leads to the relation

$$m_{\nu_{eR}} \sim k \frac{m_e^2}{m_{\nu_{eL}}} \tag{4}$$

with $k \sim 10^{-2} - 10^{2}$. Eq. (4) and the experimental upper bound[5] $m_{\nu_{eL}} < 60$ eV yield $m_{\nu_{eR}} > 4k$ GeV. We conclude that within the left-right symmetric models the right-handed electron neutrino can quite naturally acquire a Majorana mass which may be as low as a few tens MeV. The phenomenological consequences of such a mass in charged pion and kaon leptonic decays and in neutrinoless double beta-decay will be studied here. We apply this study to existing data to derive lower bounds on the mass of W_R.

A right-handed neutrino mass in the range $m_{\nu_R} < m_K$ (and $m_{\nu_R} < m_\pi$) will have three major signatures in K (and π) leptonic decays:

a) The appearance of a new spectral line in the charged lepton momentum spectrum below the familiar $m_\nu = 0$ spectral line.

b) Deviation from the theoretical value of the ratio of branching ratios $B(K,\pi\to e\nu)/B(K,\pi\to\mu\nu)$ based on massless neutrinos.

c) The polarization of the charged leptons of the secondary spectral line will be smaller than one, its magnitude and sign being determined by the mass and the right-handed nature of the massive neutrino.

These three characteristics were already discussed by Shrock[6] in a different context when studying the effects of left-handed neutrino masses and mixing angles in the charged pseudoscalar meson decays. Applying his study to existing data Shrock derives correlated bounds on the masses and mixing angles. We refer the reader to this work for a detailed description of the one-year-ago-updated related experiments.

We will disregard possible mixing angles between the right-handed mass and weak eigenstates, or alternatively assume that they are small and essentially don't affect our analysis. In our study Shrock's mixing-matrix factor $|U_{ai}|$ [6] is replaced by the ratio $(m_{W_L}/m_{W_R})^2$. We will merely discuss a single experiment from which the strongest bounds on this ratio may be extracted.

Due to the strong helicity enhancement in the decays $K,\pi\to e\nu_{eR}$ these modes are extremely sensitive to a new electron spectral line. A very recent measurement of the electron spectrum from $\pi\to e\nu$ was carried out at TRIUMF[7] and shows no secondary peak. The bound on a secondary peak is particularly stringent in the range 45 MeV < m_ν < 74 MeV, where it is found to be 0.4% relative to the primary peak. This observation

$$\frac{\Gamma(\pi\to e\nu_R)}{\Gamma(\pi\to e\nu_L)} = \left(\frac{m_{W_L}}{m_{W_R}}\right)^4 \left(\frac{m_{\nu_{eR}}}{m_e}\right)^2 \left(1-\left(\frac{m_{\nu_{eR}}}{m_\pi}\right)^2\right)^2 \leq 4\times10^{-3} \tag{5}$$

yields a lower bound on $(m_{W_R}/m_{W_L})^2$ which increases from 1200 at

$m_{\nu_{eR}}$ = 45 MeV to 1600 at 74 MeV.

A Majorana right-handed neutrino gives rise to neutrinoless double β-decay through its exchange between two neutrons in the nucleus. For a very light Majorana neutrino the amplitude for this process is proportional to m_ν, and it has been shown that existing data may set an upper bound of $m_\nu < 15$-34 eV[8,9] provided ν couples to fermions with the ordinary G_F coupling. For a heavy neutrino the amplitude contains an additional exponential Yukawa-like damping factor and depends to a certain extent on the two neutron potential. With the nuclear potential and wave function of Ref. 9 the amplitude was shown to fall off approximately like $\exp(-m_\nu/m_\pi)$ and a lower bound $m_\nu \gtrsim 2$ GeV was set based on existing data and on an assumed G_F coupling. In our case the process contains a double exchange of W_R and so the actual constraint reads

$$\left(\frac{m_{W_L}}{m_{W_R}}\right)^4 e^{-m_{\nu_{eR}}/m_\pi} \lesssim e^{-2\mathrm{GeV}/m_\pi} \tag{6}$$

We obtain a lower bound on $(m_{W_R}/m_{W_L})^2$ which falls off exponentially from about 1000 at $m_{\nu_{eR}}$ = 50-100 MeV to about 200 at $M_{\nu_{eR}}$ = 500 MeV. These lower bounds depend on the Yukawa-like damping factor which, if replaced by e.g. $\exp(-m_\nu/3m_\pi)$,[10] would lead to considerably weaker bounds.

Another phenomenological restriction on (right-handed) neutrinos in our mass range is the cosmological requirement[11] that these unstable neutrinos do not live longer than $\sim 10^4$sec. This rather conservative constraint may imply quite rough upper bounds on m_{W_R}. It is of immediate importance to determine whether these bounds are consistent with the above derived lower bounds on m_{W_R}. Here we separately consider the two distinct possibilities in which $m_{\nu_{eR}}$ lies below and above m_π.

If $m_{\nu_{eR}} < m_\pi$ the neutrino will decay into $e^- e^+ \nu_{eL}$ (and into $e^- \mu^+ \nu_{\mu L}$ if $m_{\nu_{eR}} > m_\mu + m_e$) via the exchange of W_R, W_L and $W_L - W_R$ mixing. The lifetime of this process will be

$$\tau_{\nu_{eR}} = \left(\frac{m_{W_R}}{m_{LR}}\right)^4 \left(\frac{m_\mu}{M_{\nu_{eR}}}\right)^5 \tau_\mu \tag{7}$$

The $W_L - W_R$ mixing is known to be small from the predominantly left-handed character of β decay[4] $(m_{LR}/m_{W_R})^2 < 6\times10^{-2}$. Moreover, stronger bounds on the mixing, correlated with assumed values of $m_{\nu_{eR}}$, can be derived when noting that the decay $\pi\to e\nu_{eR}$ may be induced by W_L-W_R mixing. The above-described limits from TRIUMF on a secondary electron spectral line in $\pi\to e\nu$[7] yield e.g. the bound $(m_{LR}/m_{W_R})^2 < 8\times10^{-4}$ for $45 < m_{\nu_{eR}} < 74$ MeV. In this mass domain we therefore expect $\tau_{\nu_{eR}} > 3(m_\mu/m_{\nu_{eR}})^5$ sec., which is still within the cosmological upper bound of 10^4 sec. We may turn the argument around and use the cosmological limit to set a lower bound on the W_L-W_R mixing, $(m_{LR}/m_{W_R})^2 \gtrsim 10^{-5} - 10^{-4}$ for ν_{eR} in this mass domain.

If $m_\pi < m_{\nu_{eR}} < m_K$ the lifetime due to the other possible decay mode $\nu_{eR} \to \pi e$ is given by

$$\tau_{\nu_{eR}} = 2\left(\frac{m_{W_R}}{m_{W_L}}\right)^4 \frac{m_\pi m_\mu^{\,2}(1-m^2_{\;\mu}/m^2_{\;\pi})^2}{m^3_{\nu_{eR}}\,(1-m^2_{\;\pi}/m^2_{\;\nu_{eR}})^2}\,\tau_{\pi\to\mu\nu} \tag{8}$$

The lower bound on the lifetime deduced from Eq. (8) is considerably weaker than the one deduced from Eq. (7) for $m_{\nu_{eR}} < m_\pi$ and is far from saturating the cosmological limit.

In conclusion, we have correlated the two issues of setting bounds on m_{W_R} and $m_{\nu_{eR}}$. Assuming the latter to lie within the range of 50-100 MeV, we have improved the lower bound on $(m_{W_R}/m_{W_L})^2$ by two orders of magnitude implying $m_{W_R} >$ 2-3 TeV. Future experiments of charged π and K leptonic decays are needed to provide information about yet unsearched domains. High precision $\pi \to e\nu$ and $K \to e\nu$ experiments are expected to further improve these lower bounds on m_{W_R}. An improvement by an order of magnitude in the range $m_{\nu_{eR}} < m_\pi$ would imply $\tau_{\nu_{eR}} >$ 10^4 sec., which may rule out such neutrinos by violating the cosmological limit. Finally, the phenomenologically allowed values of m_{W_R}, which are constrained to the order of 5-10 TeV, are larger by about five orders of magnitude than the assumed values of $m_{\nu_{eR}}$. This is about the ratio of m_{W_L} to m_e as speculated in the introduction and would imply that $h^M \sim h_e^D$ rather than $h^M \sim g$. Our approach was basically phenomenological. If the left-right symmetric model, which was used to motivate our study, is embedded in an SO(10) grand unified theory, the mass scale we obtain for m_{W_R} would lead to a somewhat large value of $\sin^2\theta_W = 0.26.$[12]

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